SUSY and cosmology

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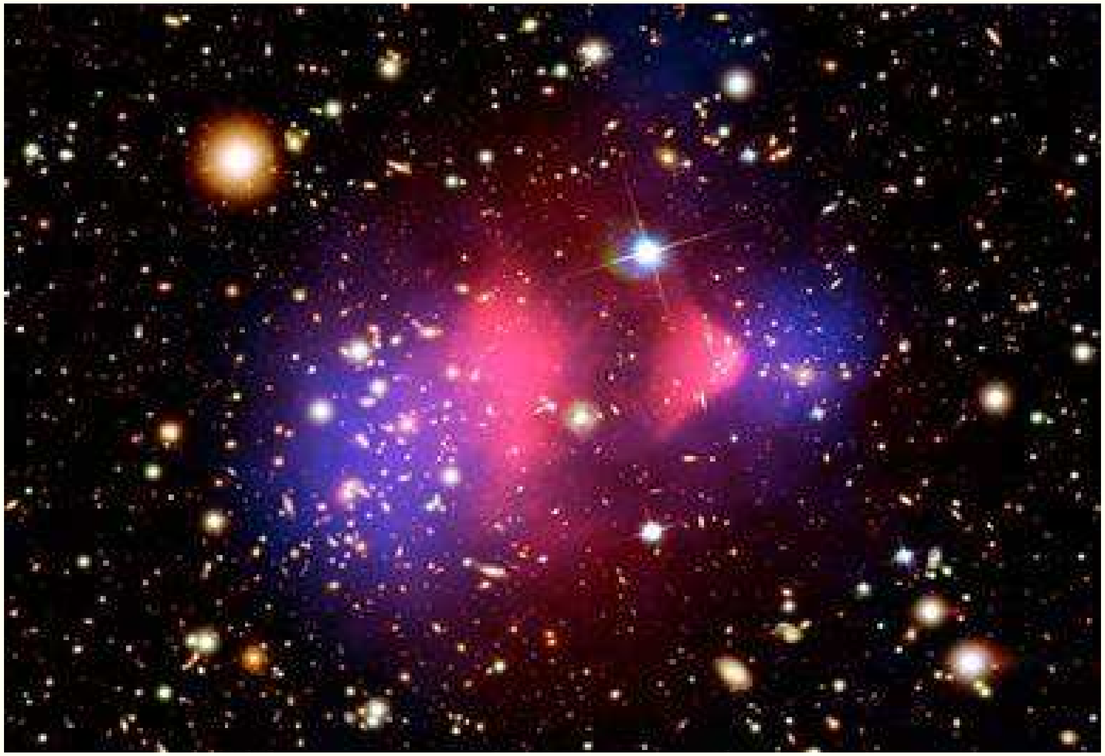
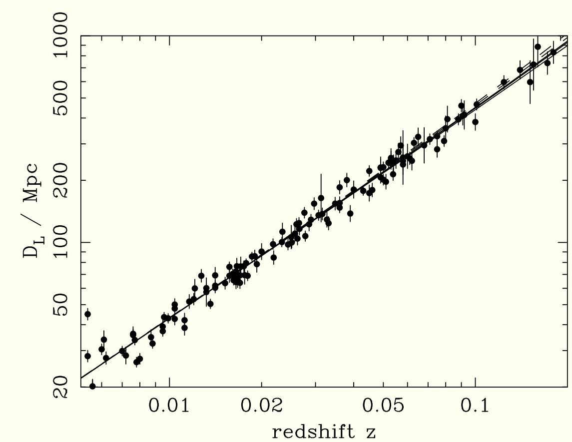
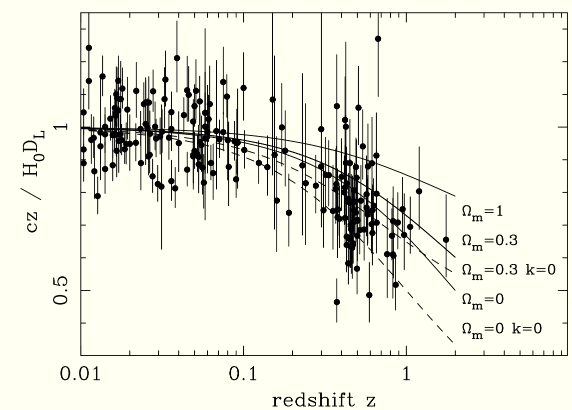


- ⋆ Cosmology
- ⋆ Baryogenesis
- ⋆ SUSY Dark matter
  - $\tilde{\chi}, \tilde{a}, \tilde{G}$
- ⋆ models
  - mSUGRA
  - NUSUGRA
  - MM-AMSB
  - $SO(10)$ SUSYGUTs

Pillars of Big Bang cosmology: Hubble expansion

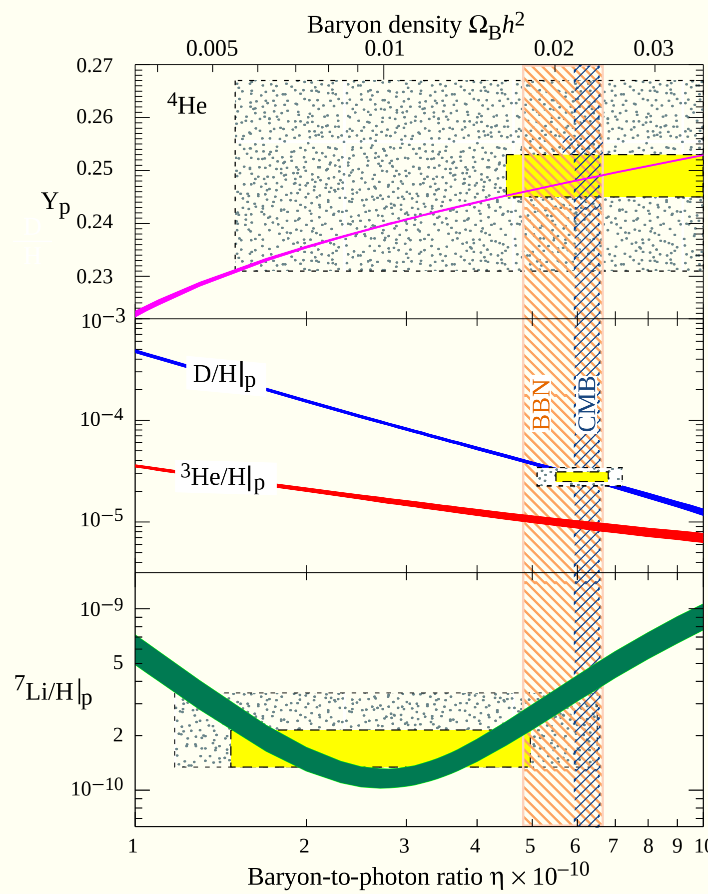
- Theory: FRW universe
- Hubble expansion
  - HST key project
  - type Ia supernovae probe
- $H_0 d_L = z + \frac{1}{2}(1 - q_0)z^2 + \cdots$
- $H_0 = 72$ km/sec/Mpc$\pm 10\%$
- evidence for $\Lambda > 0$!
- age of universe: ~ 13.7 Gyrs





Big Bang nucleosynthesis (BBN)

- ⋆ Thermal history of universe:
- ⋆ Can compute light element abundances: ^4He, D, ^3He, ^7Li
  - match to data:
  - $\eta_B \equiv \frac{n_B}{n_\gamma} \simeq 6\times 10^{-10}$
  - η_B from BBN consistent with CMB results



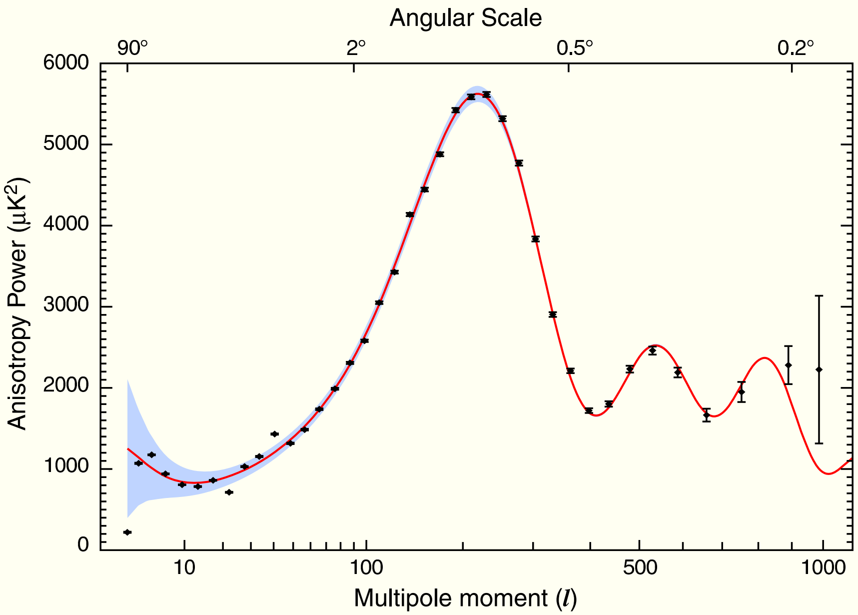
Cosmic microwave background (CMB)

⋆ COBE/WMAP/WMAP3, $\cdots$

⋆ anisotropies $\sim 10^{-5}$

⋆ can extract numerous cosm. param's from power spectrum

- flat $(k = 0)$ universe: $\rho = \rho_c$ as in inflation models
- contents of universe
  - $\Omega_\Lambda \sim 0.7$
  - $\Omega_{baryons} \sim 0.04$
  - $\Omega_{CDM} \sim 0.25$
  - $\Omega_\nu \sim tiny$

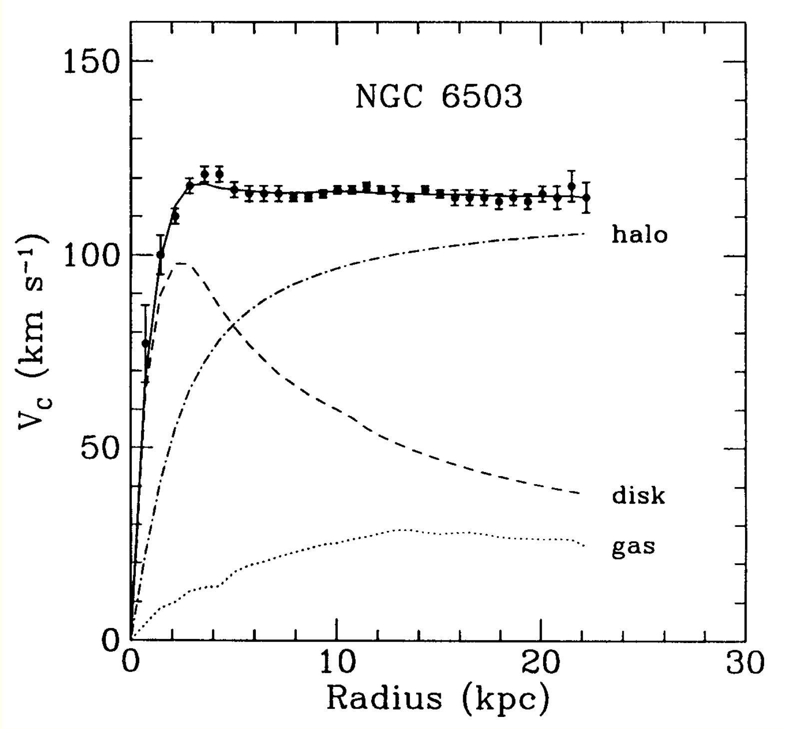


Baryogenesis: explaining η_B

- ⋆ SM electroweak baryogenesis: only if $m_{H_{SM}} \lesssim 50$ GeV
- ⋆ MSSM: many more possibilities
  - EW baryogenesis: need $m_{\tilde{t}_1} < m_t$; $m_h \lesssim 120$ GeV (Carena et al.)
  - Affleck-Dine: decay of flat directions: baryo- or leptogenesis
  - thermal leptogenesis: (Fukugita, Yanagida; Buchmueller, Plumacher, ...)
    - ∗ natural link to physics of massive neutrinos
    - ∗ due to decay of heavy N states: $N \to H\ell \neq N \to H^\dagger \bar{\ell}$
    - ∗ lepton asymmetry converted to baryon asymmetry via sphaleron effects
    - ∗ get $\eta_B \sim 6 \times 10^{-10}$ if $M_N \sim 10^{10}$ GeV
    - ∗ need reheat temp $T_R \sim 10^{10}$ GeV
    - ∗ overproduction of gravitinos if $.1 \lesssim m_{\tilde{G}} \lesssim 10$ TeV
  - leptogenesis via inflaton decay
- ⋆ can be constrained by ν/sparticle measurements

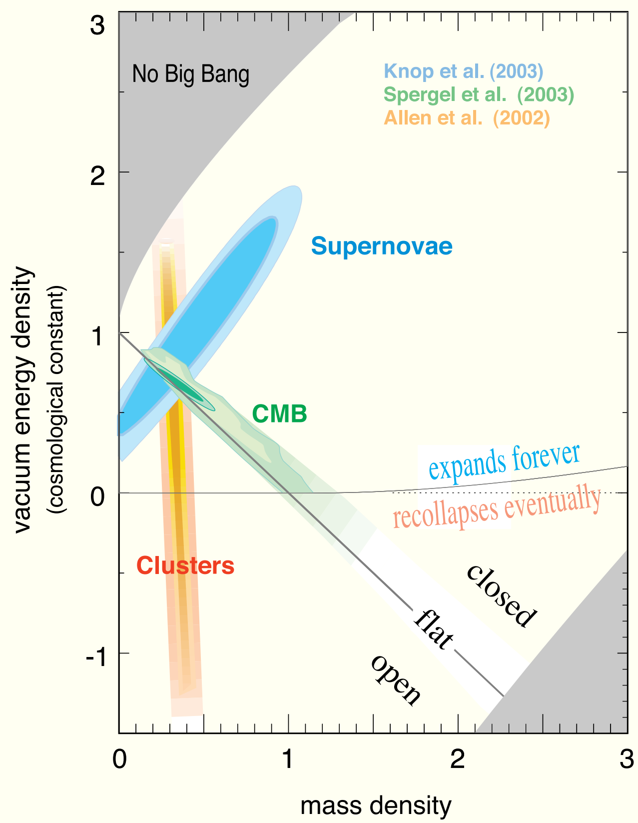
Dark Matter in the universe

- ⋆ Binding of clusters
- ⋆ Galactic rotation curves
- ⋆ Gravitational lensing
- ⋆ Hot gas in clusters
- ⋆ CMB fluctuations
- ⋆ Large scale structure
- ⋆ flatness/BBN



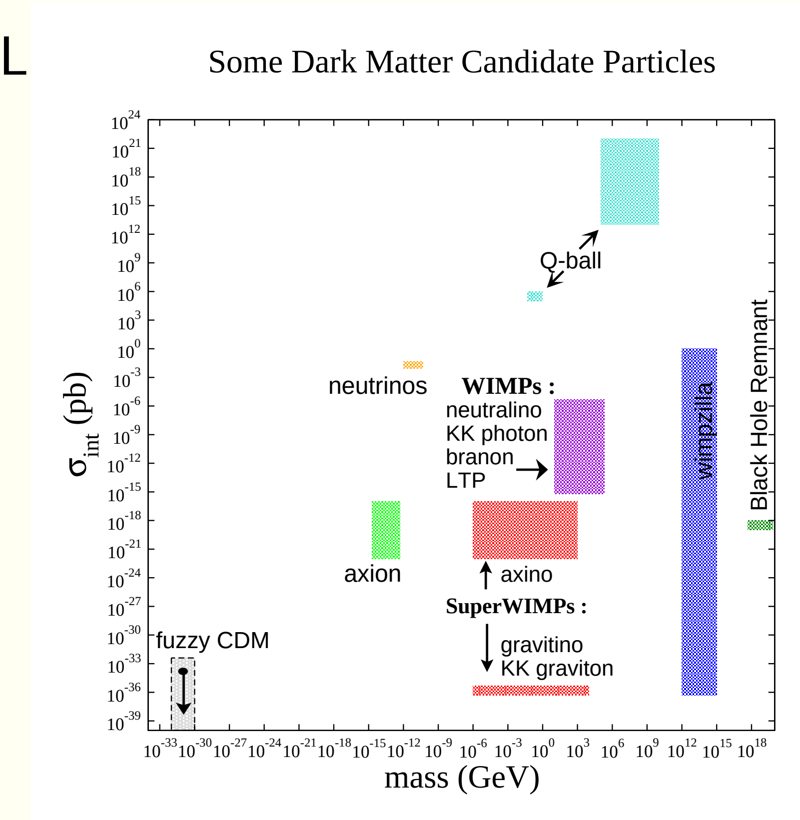
Best fit cosmology: concordance (ΛCDM) model

- $\Omega_B h^2 = 0.022 \pm 0.001$
- $\Omega_\nu h^2 < 0.007 \;\; 95\% \; CL$
- $\Omega_\Lambda h^2 \sim 0.38 \pm 0.03$
- $\Omega_{CDM} h^2 = 0.105 \pm 0.01$



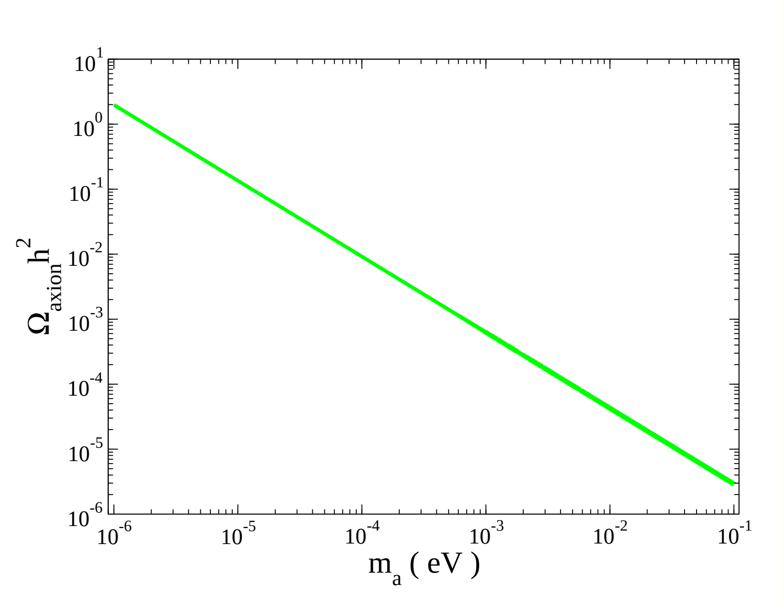
Candidates for Dark Matter

- ⋆ unseen baryons, e.g. BHs, brown dwarves, stellar remnants
  - – inconsistent with BBN element abundance calc'n
  - – limits from MACHO, EROS, OGL
- ⋆ light neutrinos $(= HDM)$
- ⋆ axions/axinos
- ⋆ WIMPS
- ⋆ superWIMPS
- ⋆ Q-balls
- ⋆ primordial BHs



Axions

- ⋆ PQ solution to strong CP problem in QCD
- ⋆ pseudo-Goldstone boson from PQ breaking at scale f_a
- ⋆ non-thermally produced via vacuum mis-alignment

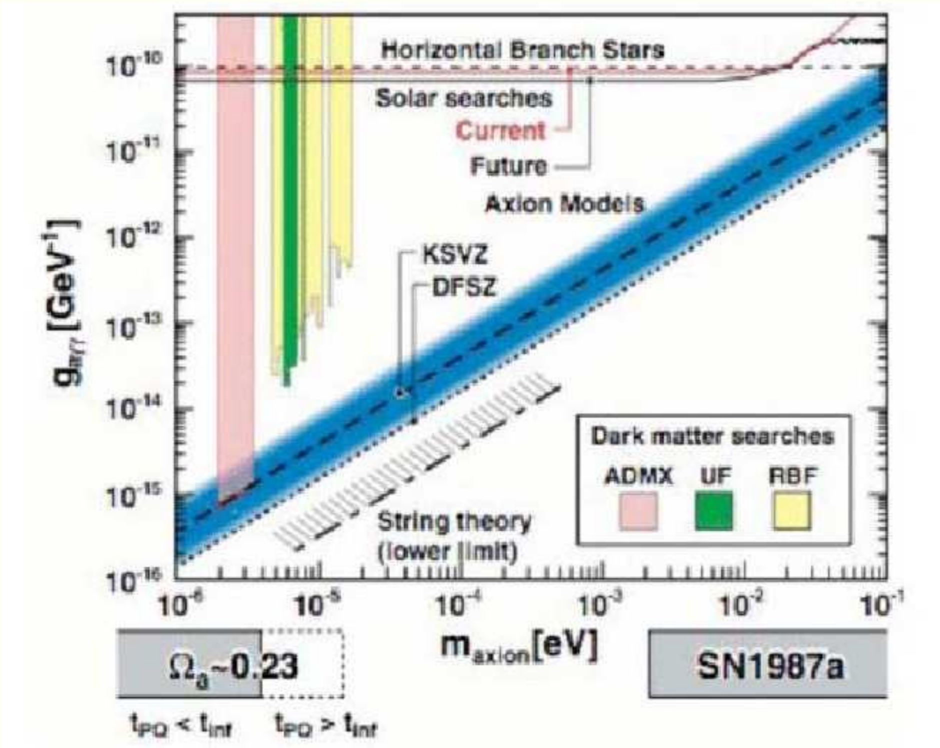


  - $m_a \sim \Lambda^2_{QCD}/f_a \sim 10^{-6} - 10^{-1} eV$
  - $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times 10^{-6} eV}{m_a}\right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-1} eV$
  - a couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches

Axion microwave cavity searches

⋆ ongoing searches: ADMX experiment

- Livermore⇒ U Wash.
- Phase I: probe KSVZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- Phase II: probe DFSZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- beyond Phase II:
  probe higher values m_a

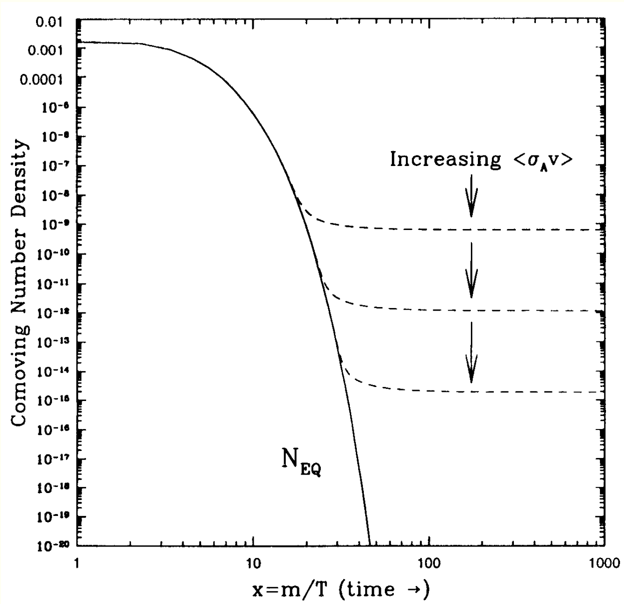


WIMPs: the WIMP miracle!

- Weakly Interacting Massive Particles
- assume in thermal equil'n in early universe
- Boltzman eq'n:

$$-\ dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$$

- $\Omega h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*}\right)^{1/2} \frac{x_f}{M_{Pl}} \frac{1}{\langle \sigma v \rangle}$
- $\sim \frac{0.1\ pb}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{m_{wimp}}{100\ GeV}\right)^2$
- thermal relic $\Rightarrow$ new physics at M_{weak}!



Some WIMP candidates

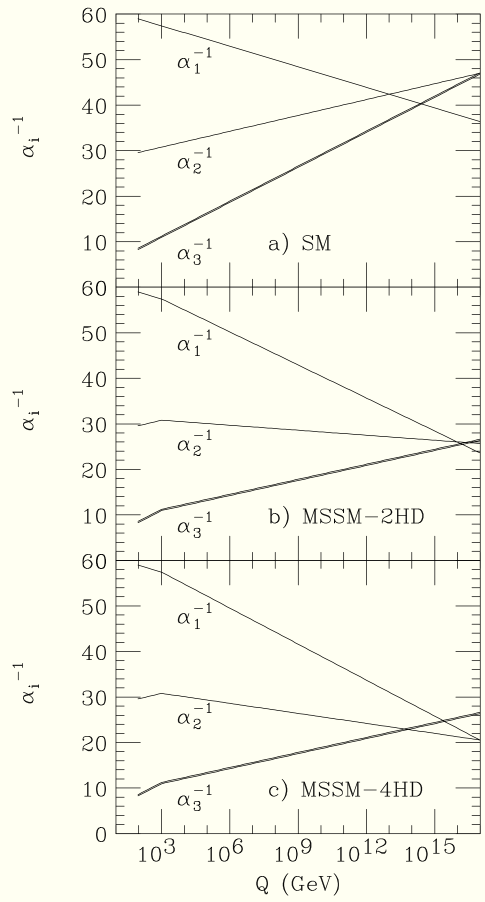
- ⋆ 4th gen. Dirac ν (excluded)
- ⋆ SUSY neutralino (χ or $\widetilde{Z}_1$)
- ⋆ UED excited photon B_μ^1
- ⋆ little Higgs photon B_H
- ⋆ little Higgs (theory space) N_1 (scalar)
- ⋆ warped GUTS: LZP KK fermion
- ⋆ branons
- ⋆ $\cdots$

Most work done for SUSY theories

- ⋆ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ⋆ gauge coupling unification!
- ⋆ Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!
- ⋆ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
- ⋆ dark matter candidate: lightest neutralino $\tilde{Z}_1$
- ⋆ stable see-saw mechanism for neutrino mass
- ⋆ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis
  - most analyses: mSUGRA model
    - $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
  - lots and lots of other models

Supersymmetry: fermions⇔ bosons

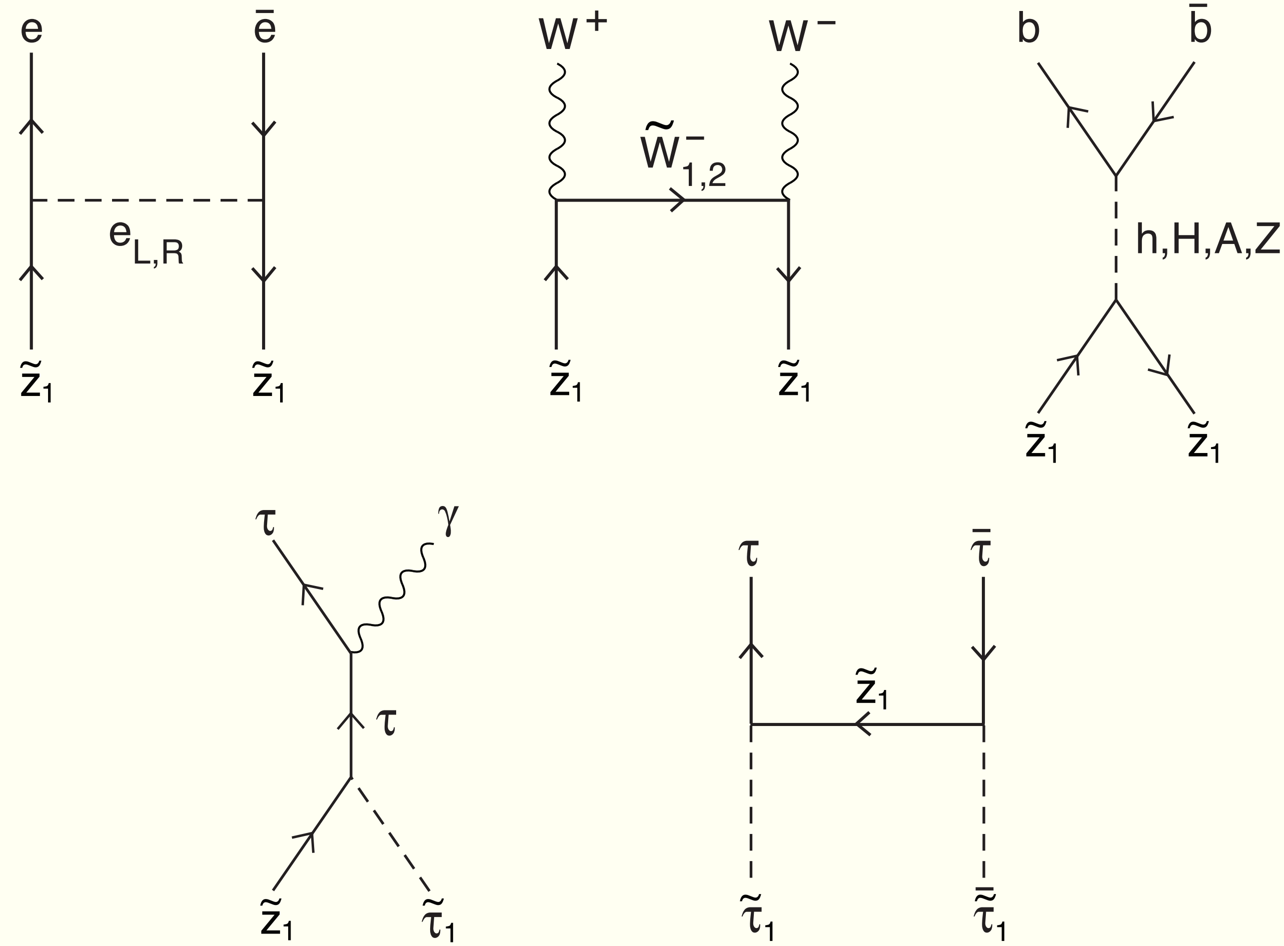
- ⋆ MSSM: doubling of spectra
  - spin-0 squarks, sleptons
  - spin-$\frac{1}{2}$ charginos, neutralinos, gluino
  - extra Higgses: $h,\ H,\ A,\ H^{\pm}$
  - R-parity cons'n: LSP is stable
- ⋆ LSP candidates
  - sneutrinos (excluded)
  - gravitinos (superWIMPs)
  - neutralinos
  - GMSB messengers
  - hidden sector states
  - axinos $\tilde{a}$



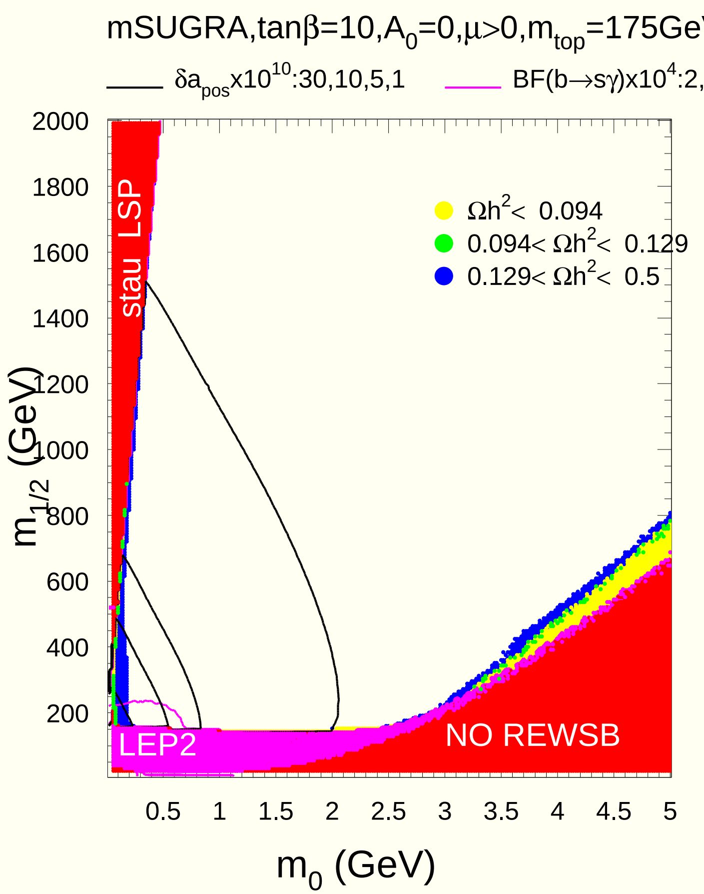
Neutralino dark matter

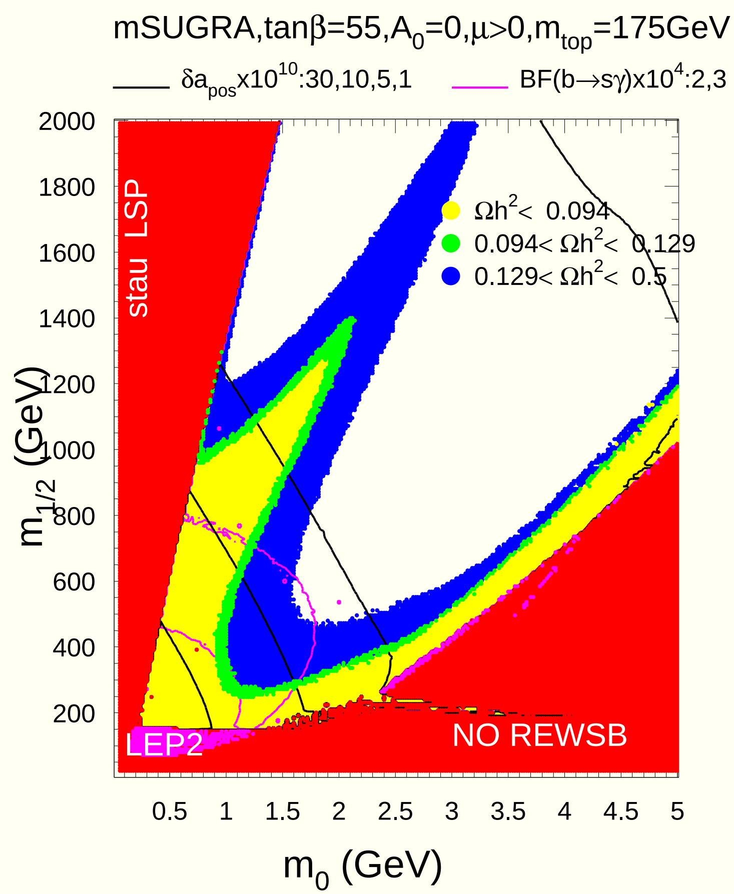
- ⋆ Why R-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin, Kawamura, $\cdots$)
- ⋆ In thermal equilibrium in early universe
- ⋆ As universe expands and cools, freeze out
- ⋆ Number density obtained from Boltzmann eq'n
  - $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
  - depends critically on thermally averaged annihilation cross section times velocity
- ⋆ many thousands of annihilation/co-annihilation diagrams
- ⋆ several computer codes available
  - DarkSUSY, Micromegas, IsaReD (part of Isajet)

Some neutralino (co)annihilation processes



Relic density in minimal SUGRA model



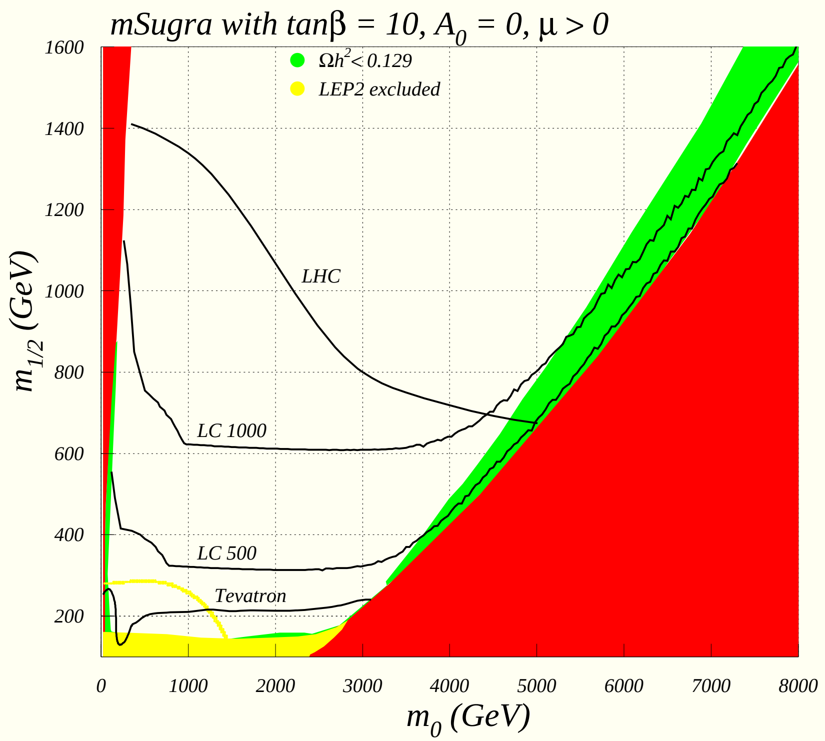


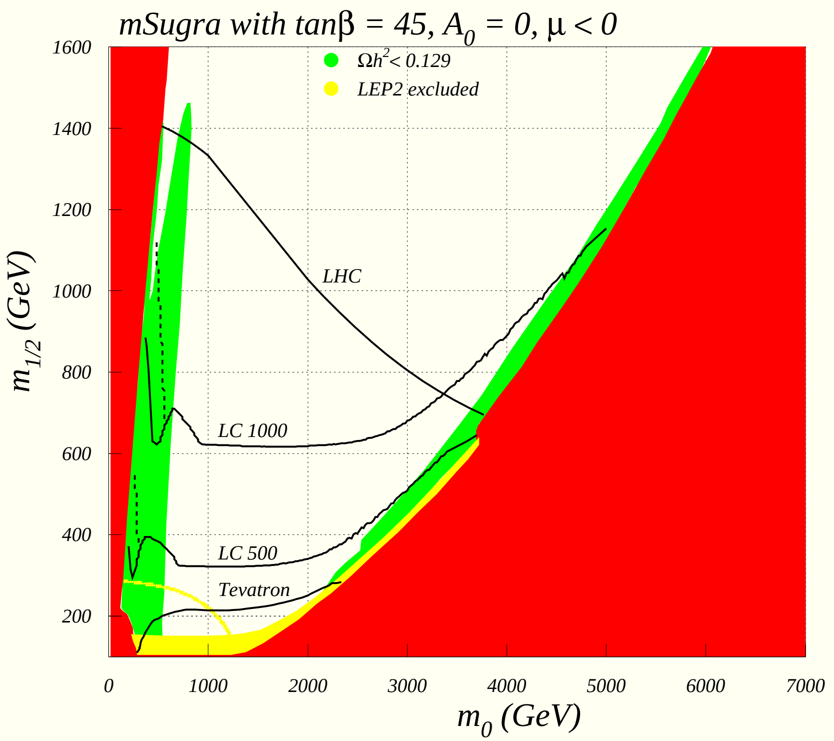
HB, A. Belyaev, T. Krupovnickas and A. Mustafayev

Main mSUGRA regions consistent with WMAP

- ⋆ bulk region (low m_0, low $m_{1/2}$)
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
- ⋆ HB/FP region (large m_0 where $|\mu| \to small$)
- ⋆ A-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
- ⋆ h corridor ($2m_{\widetilde{Z}_1} \simeq m_h$)
- ⋆ stop co-annihilation region (particular A_0 values $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

SUSY reach of all colliders and relic density





HB, Belyaev, Krupovnickas, Tata

International linear e^+e^- collider (ILC)

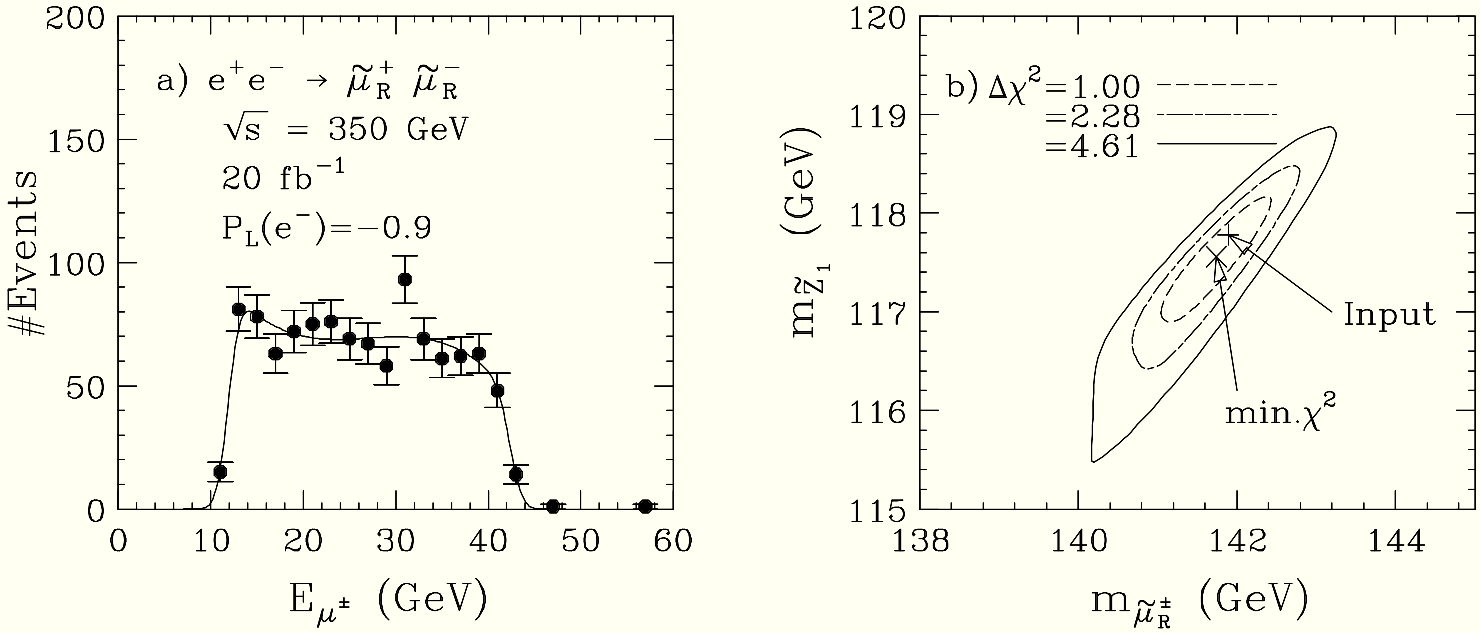
⋆ A linear e^+e^- collider with $\sqrt{s} = 0.5 - 1$ TeV is highest priority project for HEP beyond LHC! Why?

- All beam energy ⇒ collision (aside from brem/beamstrahlung losses)
- beam energy known
- clean collision environment
- low (electroweak) background levels
- adjustable beam energy (threshold scans)
- e^- and possibly e^+ beam polarization

⋆ ILC will be *ideal* machine to perform precision spectroscopy of any new (EW interacting) matter states (provided they are kinematically accessible)!

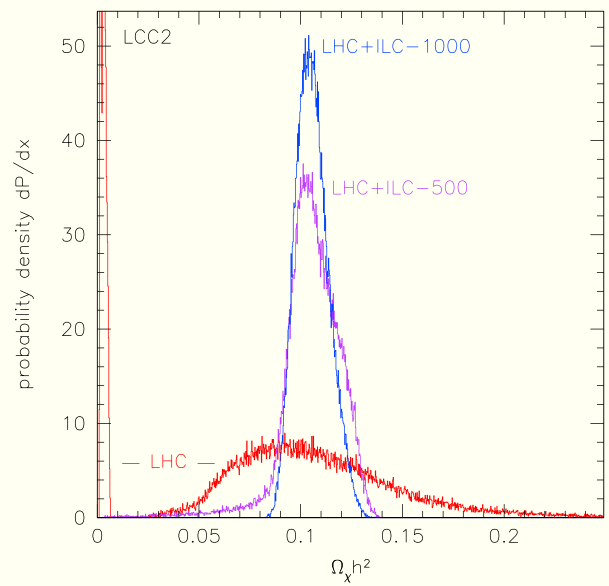
⋆ timeline: decision-2012; ready-2020

Precision sparticle measurements at a e^+e^- linear collider



Role of ILC in DM physics

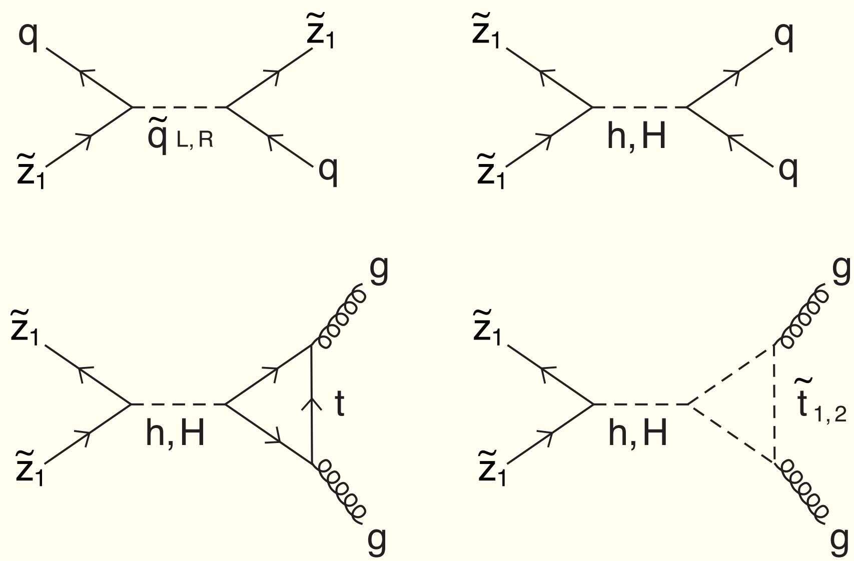
- Baltz, Battaglia, Peskin, Wizansky analysis
- fit all sparticle measurements to determine underlying SUSY parameters
- then plug in to theory to find relic density
- does $\Omega_{\widetilde{Z}_1} h^2$ saturate measured value?
- possible mixed dark matter? $\widetilde{Z}_1$ decay to gravitino or axino?



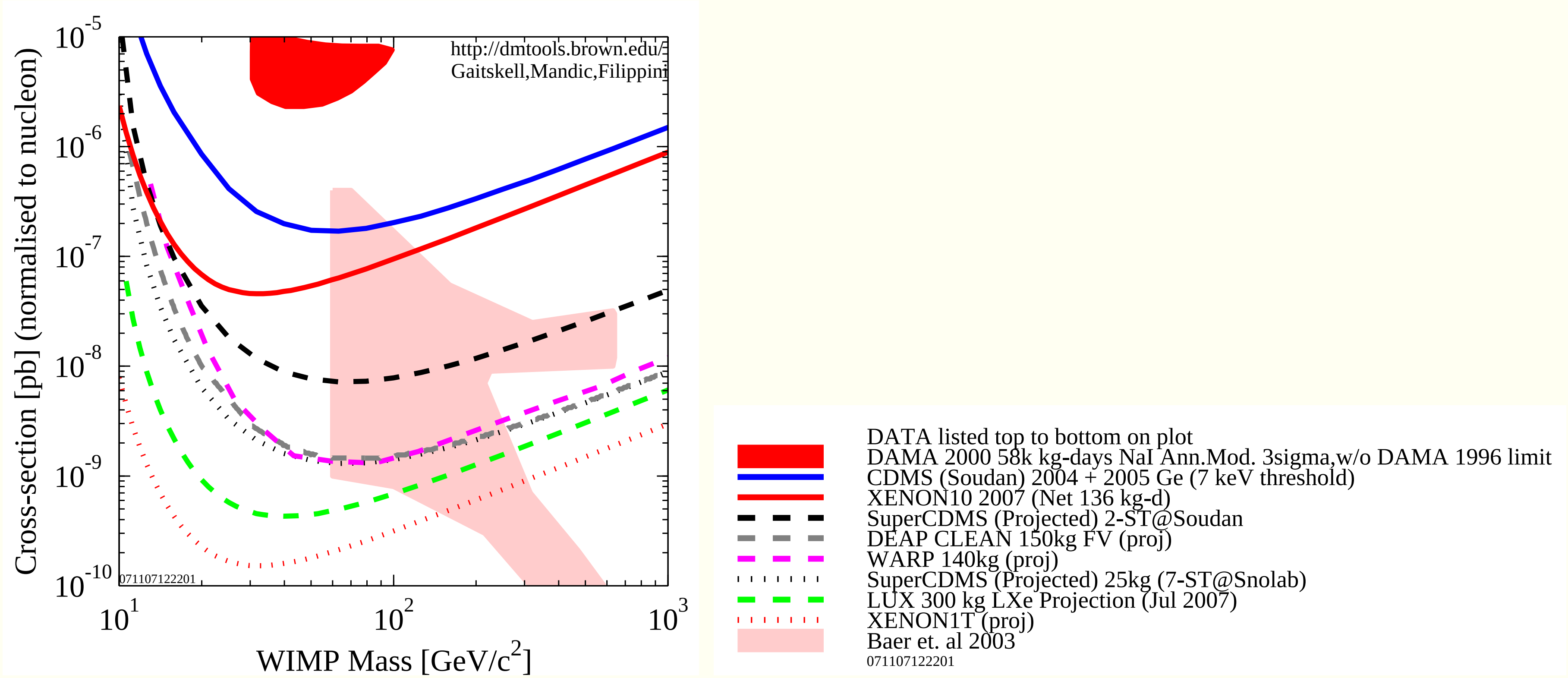
Direct detection of SUSY DM

★ Calculate neutralino-nucleus scattering

- calculate $\widetilde{Z}_1 - q$ or $\widetilde{Z}_1 - g$ scattering: take $v \to 0$ limit
  - ∗ spin-dependent cross section couples to spin of nucleus: cancel
  - ∗ spin-independent cross section $\propto A^2$: add
  - ∗ results usually quoted in terms of $\sigma_{SI}(\widetilde{Z}_1 p)$ so results from different target nuclei can be compared

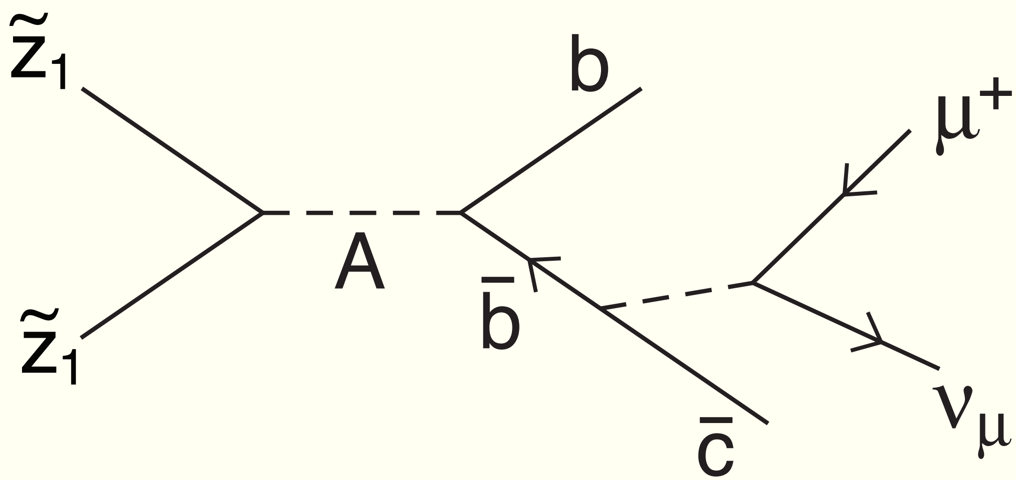


Current best limit: new Xenon-10 result!



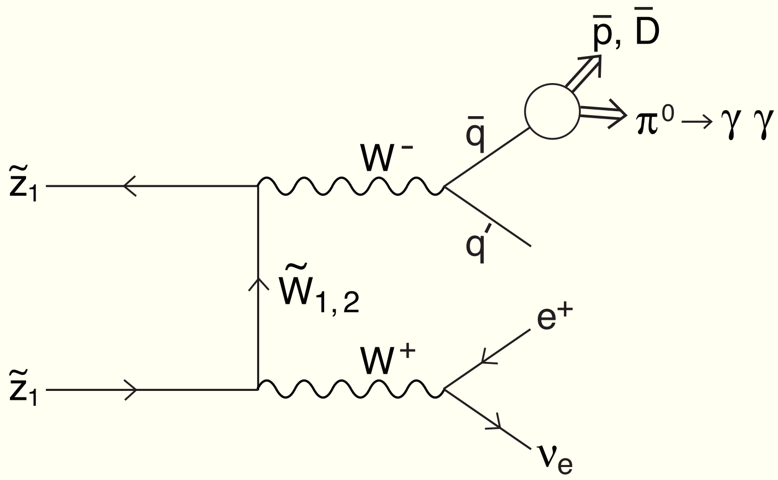
Indirect detection (ID) of SUSY DM: ν-telescopes

- $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes
- flux is largest when $\sigma(\widetilde{Z}_1 p)$ is largest
  - $e.g.$ low $m_{\tilde{q}}$ or HB/FP region for mSUGRA
  - experiments: Amanda, Icecube, Antares

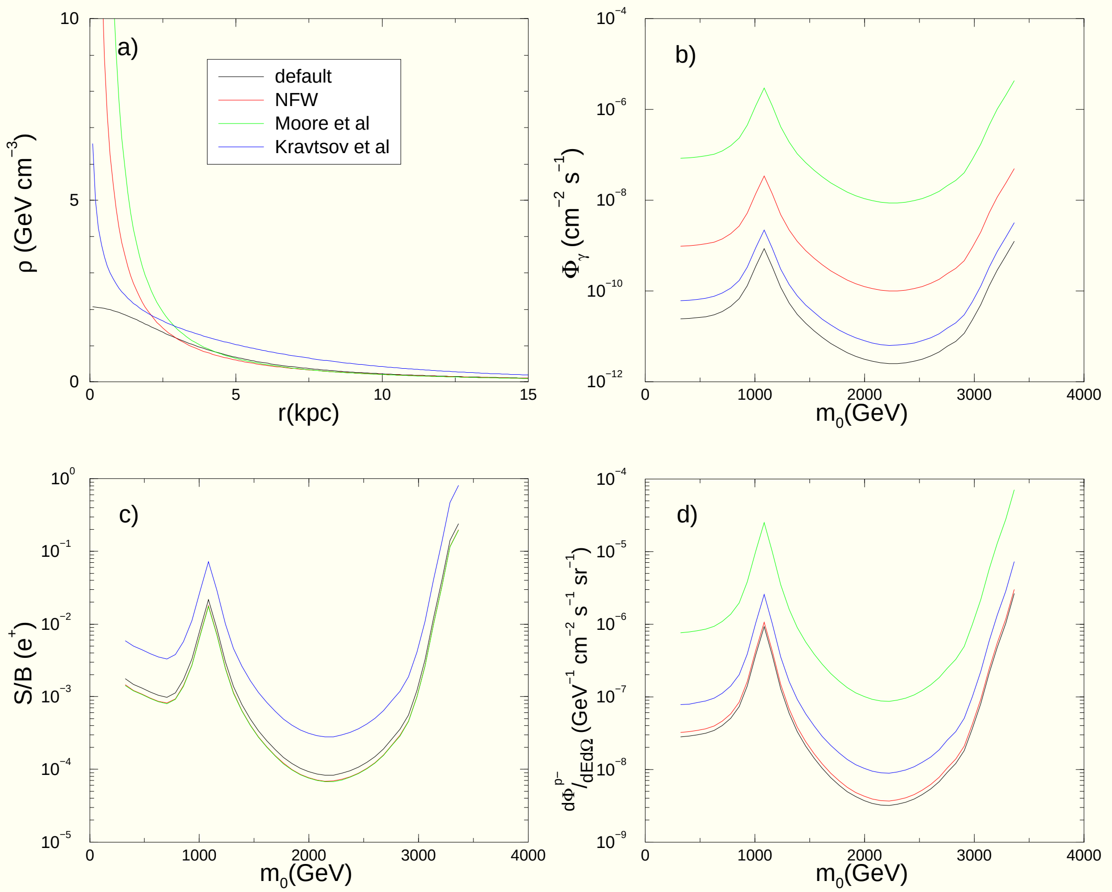


ID of SUSY DM: γ and anti-matter searches

- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ in galactic core or halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to e^+$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{p}$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{D}$ in galactic halo

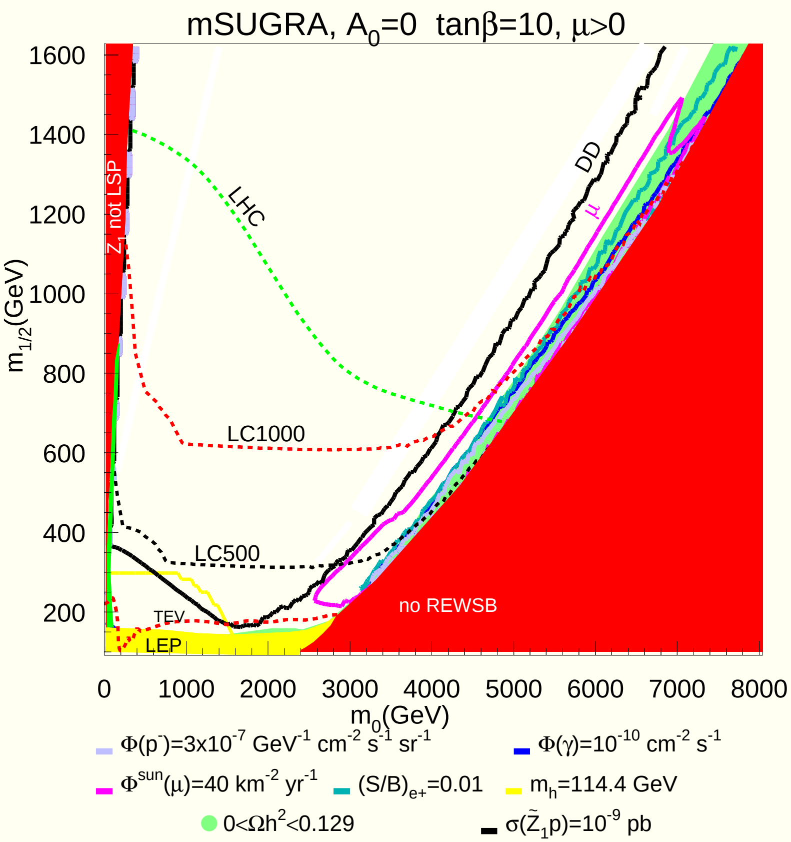


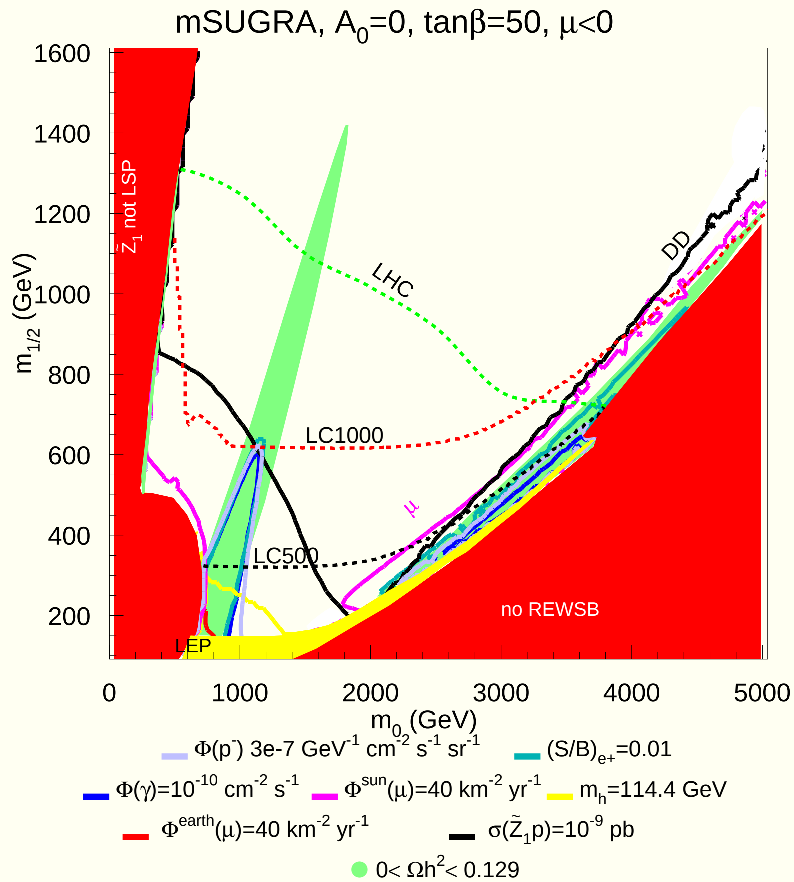
Rates for γs, e^+s, $\bar{p}$s vs. m_0 for fixed $m_{1/2} = 550$ GeV, $\tan\beta = 50$



- rates enhanced in A-funnel and HB/FP region (MHDM)

Direct and indirect detection of neutralino DM





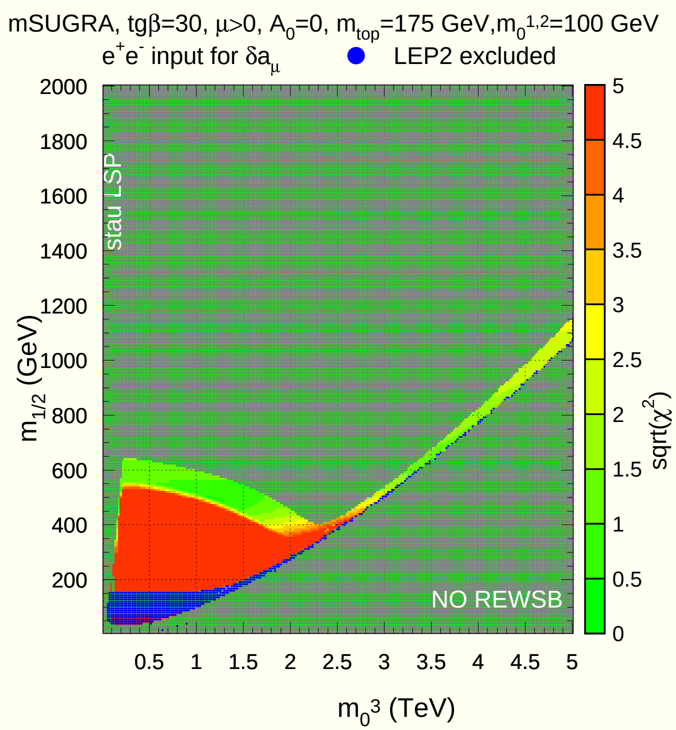
HB, Belyaev, Krupovnickas, O'Farrill

SuperWIMPs (e.g. $\tilde{G}$ in SUGRA or G in UED)

- ⋆ $m_{\tilde{G}} = F/\sqrt{3}M_* \sim$ TeV in Supergravity models
  - usually $\tilde{G}$ decouples (but see Moroi et al. for BBN constraints)
  - if $\tilde{G}$ is LSP, then calculate NLSP abundance as a thermal relic: $\Omega_{NLSP}h^2$
  - $\widetilde{Z}_1 \to h\tilde{G},\ Z\tilde{G},\ \gamma\tilde{G}$ or $\tilde{\tau}_1 \to \tau\tilde{G}$ possible
    - ∗ lifetime $\tau_{NLSP} \sim 10^4 - 10^8$ sec
    - ∗ constraints from BBN, CMB not too severe
    - ∗ DM relic density is then $\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}}\Omega_{NLSP} + \Omega_{\tilde{G}}^{TP}(T_R)$
    - ∗ Feng, Rajaraman, Su, Takayama; Ellis et al; Buchmuller et al.
  - $\tilde{G}$ undetectable via direct/indirect DM searches
  - unique collider signatures:
    - ∗ $\tilde{\tau}_1$=NLSP: stable charged tracks
    - ∗ can collect NLSPs in e.g. water (slepton trapping)
    - ∗ monitor for $NLSP \to \tilde{G}$ decays

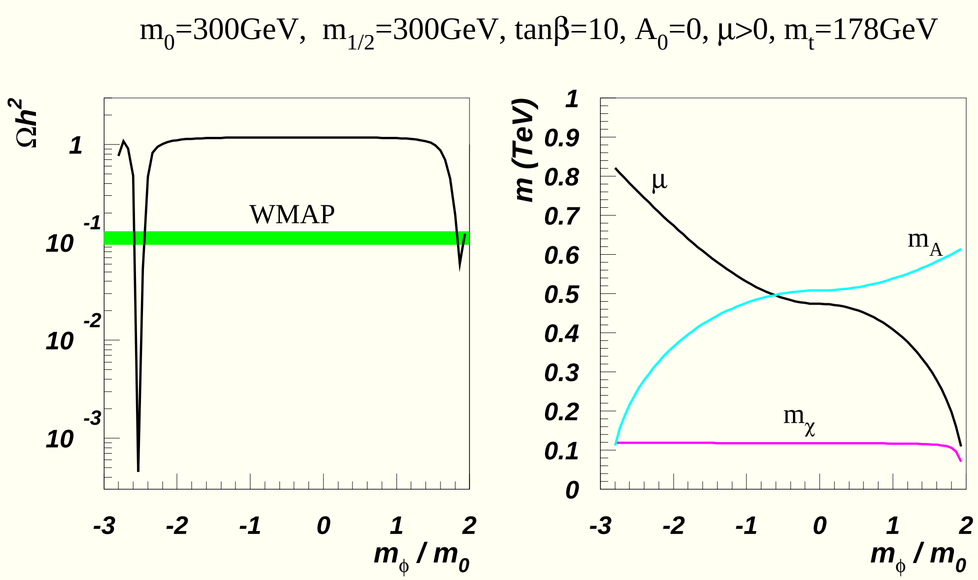
SUGRA models with non-universal scalars

- Normal scalar mass hierarchy NMH: HB, Belyaev, Krupovnickas, Mustafayev
- $m_0(1) \simeq m_0(2) \ll m_0(3)$ (preserve FCNC bounds)
- motivation: reconcile $BF(b \to s\gamma)$ with $(g-2)_\mu$ anomaly



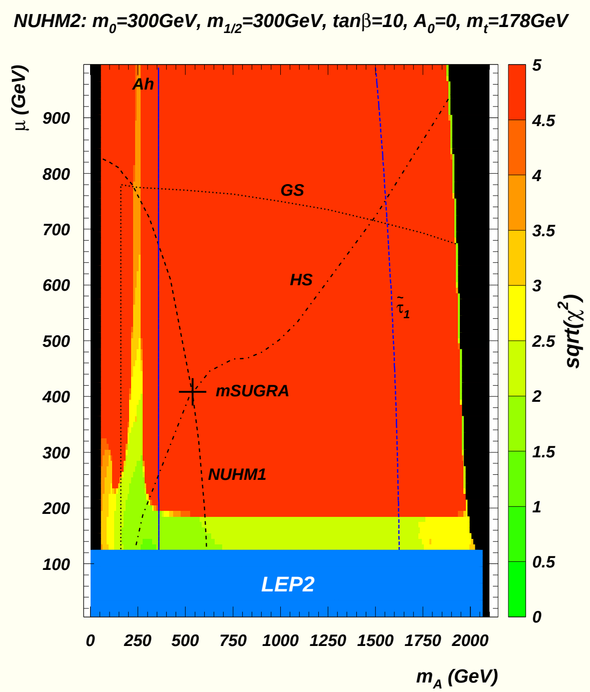
SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SO(10)$ SUSYGUTs where $\hat{H}_{u,d} \in \phi(10)$ while matter $\in \psi(16)$
- $m_\phi^2 \gg m_0$ $\Rightarrow$higgsino DM for any $m_0,\ m_{1/2}$
- $m_\phi^2 < 0 \Rightarrow$ can have A-funnel for any $\tan\beta$



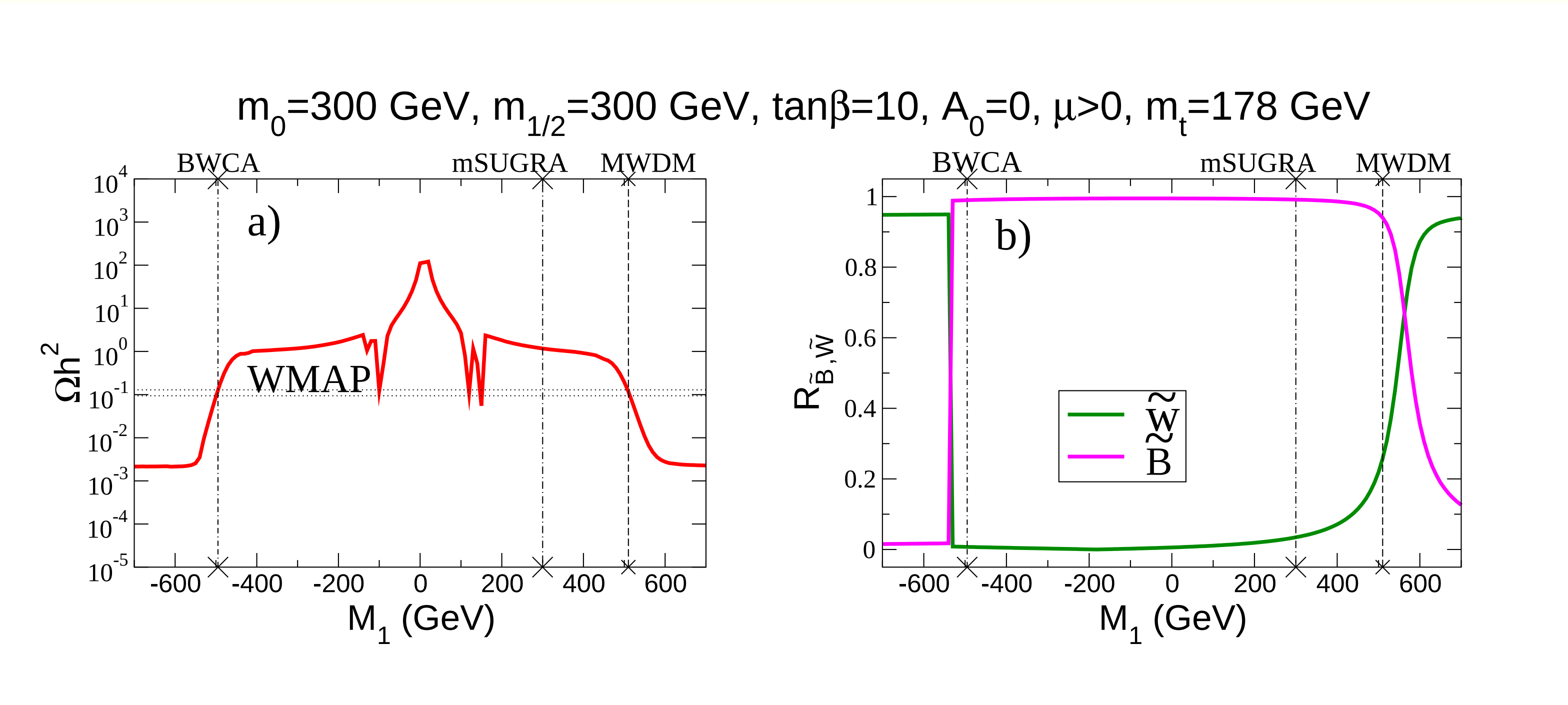
NUHM2 (2-parameter case)

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0$: HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SU(5)$ SUSYGUTs where $\hat{H}_u \in \phi(5)$, $\hat{H}_d \in \phi(\bar{5})$
- can re-parametrize $m_{H_u}^2,\ m_{H_d}^2 \leftrightarrow \mu,\ m_A$ (Ellis, Olive, Santoso)
- large S term in RGEs $\Rightarrow$ light $\tilde{u}_R,\ \tilde{c}_R$ squarks, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$



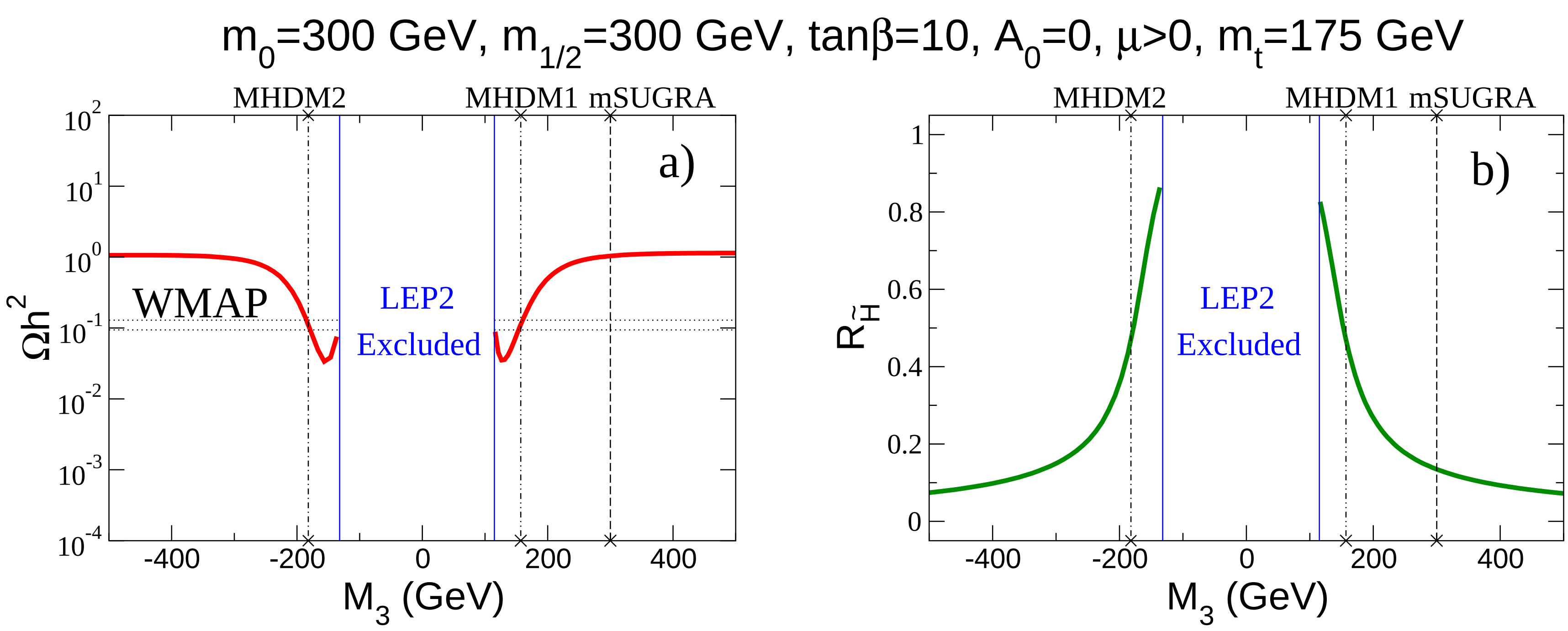
Gaugino mass non-universality

- $M_1 \neq M_2 \neq M_3$: HB, TK, AM, EP, SP, XT
- motivation: SUSYGUTs where gauge kinetic function transforms non-trivially
- $M_2 \sim M_1$ at M_{GUT}: mixed wino dark matter (MWDM)
- $M_2 \simeq -M_1$ at M_{GUT}: bino-wino co-annihilation (BWCA)

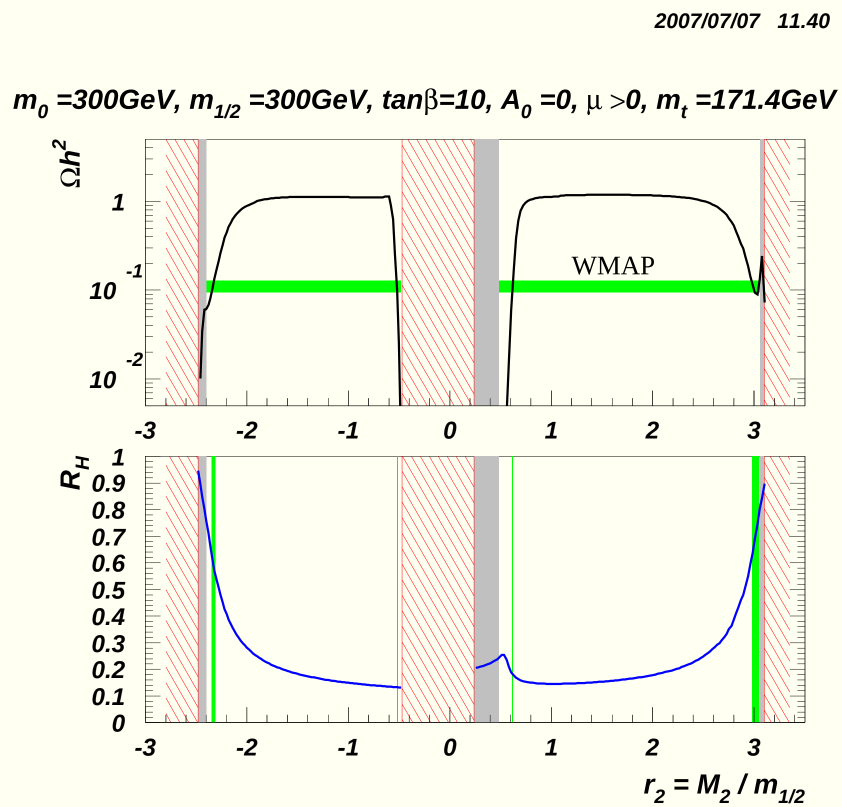


Gaugino mass non-universality: low M_3 case

- $M_3 < M_1 \sim M_2$: HB, TK, AM, EP, SP, XT
- motivation: mixed-moduli AMSB models
- lower $M_3 \to$ low $m_{\tilde{q}} \to$ low $\mu \to$ mixed higgsino DM



Mixed higgsino DM from a high M_2 (HM2DM)



- high $M_2 \Rightarrow$ low $|\mu|$ so get mixed higgsino DM but high $m_{\tilde{q}_L}$
- HB, Mustafayev, Summy, Tata

Compressed SUSY (Steve Martin)

- in models with low M_3 and $A_0 \sim -M_1$, the $\tilde{t}_1$ becomes quite light
- Martin finds that if
  - $m_t < m_{\widetilde{Z}_1} \lesssim m_t + 100$ GeV and
  - $m_{\widetilde{Z}_1} + 25 \text{ GeV} \lesssim m_{\tilde{t}_1} \lesssim m_{\widetilde{Z}_1} + 100$ GeV, then
- $\widetilde{Z}_1 \widetilde{Z}_1 \to t\bar{t}$ is dominant dark matter annihilation mechanism in early Universe!
- implications for LHC, DD, IDD: (HB, Box, Park, Tata)
  - light $m_{\tilde{g}}$ with $\tilde{t}_1 = NLSP$
  - collider signatures depend on whether $\tilde{t}_1 \to c\widetilde{Z}_1$ or $bW\widetilde{Z}_1$
  - if $\tilde{t}_1 \to c\widetilde{Z}_1$, then large $\not{E}_T + jets$, but very low isolated lepton rates
  - IDD halo annihilation signals enhanced since $\widetilde{Z}_1 \widetilde{Z}_1 \to t\bar{t} \to \gamma$s, anti-matter

Mixed modulus-AMSB models

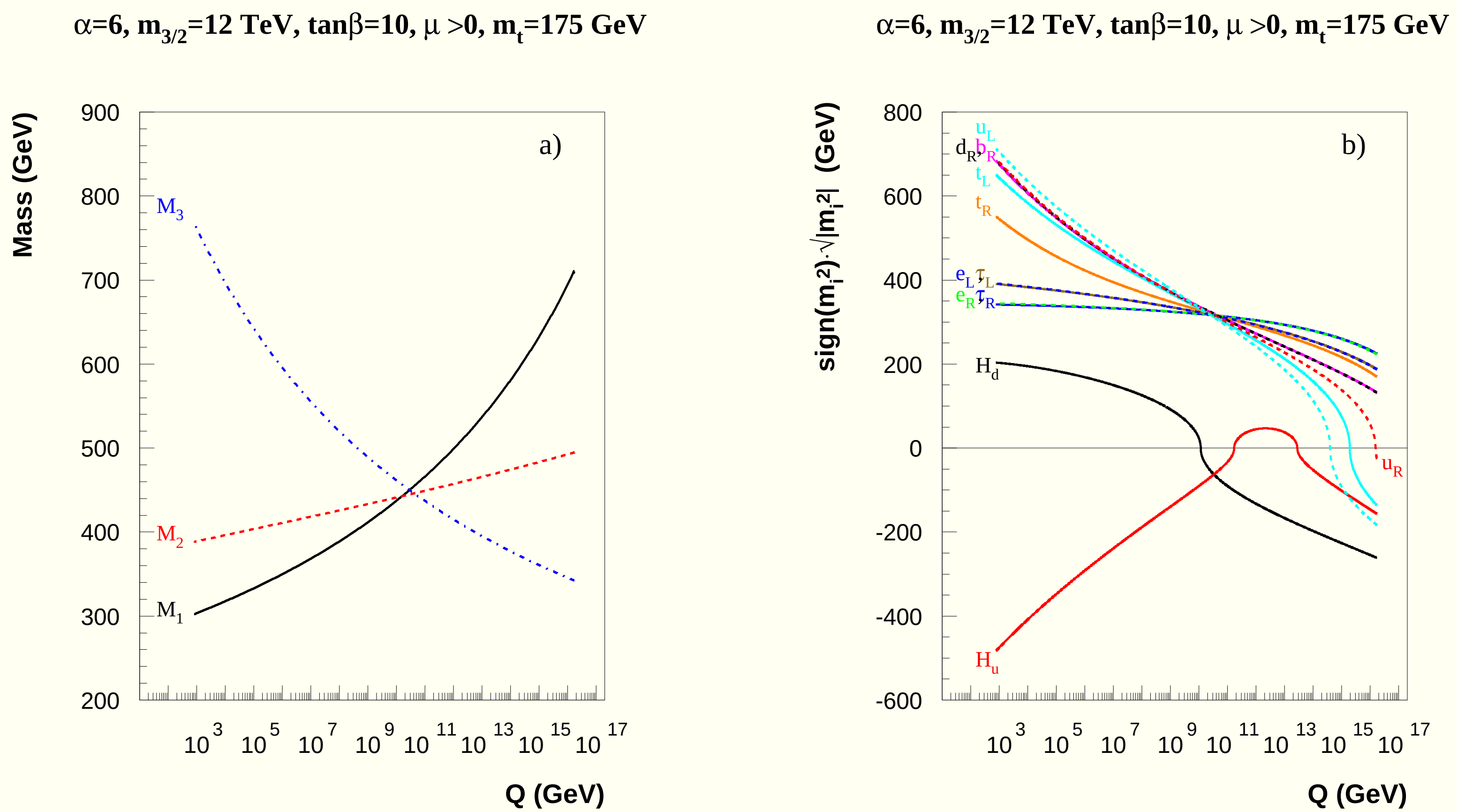
⋆ KKLT model: type IIB superstring compactification with fluxes

- stabilize moduli/dilaton via fluxes and e.g. gaugino condensation on $D7$ brane
- introduce anti-$D3$ brane (uplifting potential; de Sitter universe with $\Lambda > 0$
- small SUSY breaking due to $\overline{D3}$ brane
- mass hierarchy: $m_{moduli} \gg m_{3/2} \gg m_{SUSY}$

⋆ MSSM soft terms calculated by Choi, Falkowski, Nilles, Olechowski, Pokorski

⋆ phenomenology: Choi, Jeong, Okumura; Falkowski, Lebedev, Mambrini; Kitano, Nomura

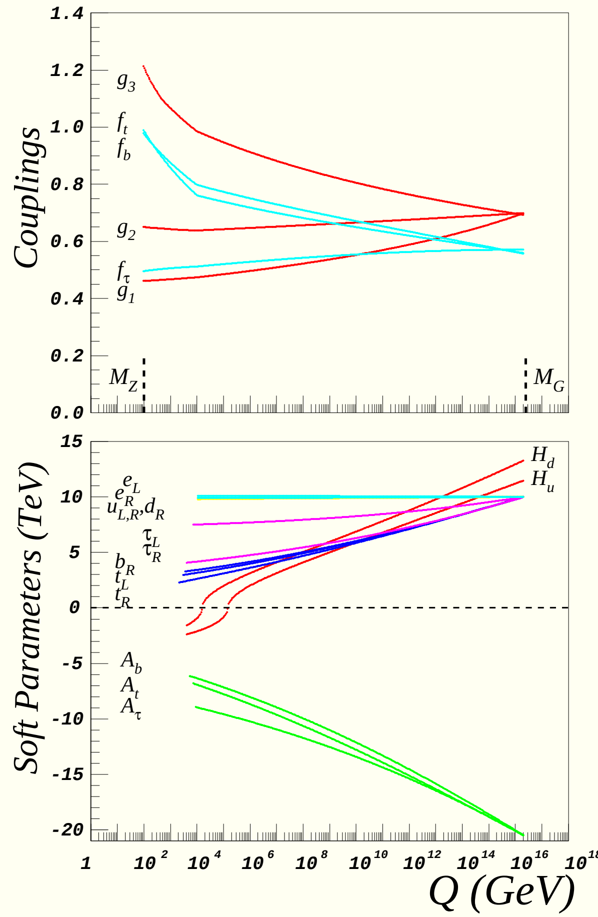
⋆ see also: HB, E. Park, X. Tata, T. Wang, JHEP**0608**, 041 (2006); PL**B641**, 447 (2006); JHEP**0706**, 033 (2007);



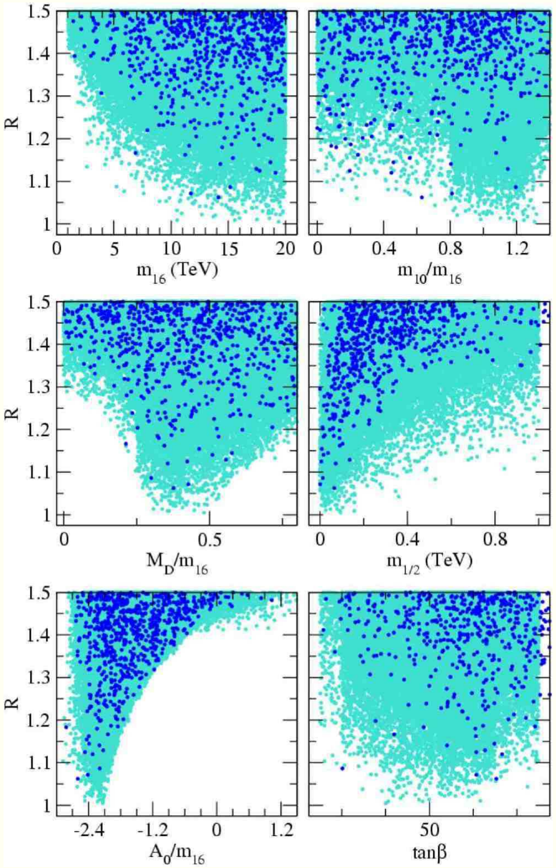
- GUT scale AMSB splitting of soft terms cancelled by RGE running: soft terms unify at "mirage" unification scale
- MM-AMSB contains BWCA, MWDM, LM3DM scenarios!

$SO(10)$ SUSYGUTs and $t-b-\tau$ Yukawa unification (YU)

- superpotential:
  - $\hat{f} \ni f\psi_{16}\psi_{16}\phi_{10} + \cdots$
- YU not possible in mSUGRA
- YU can work in NUHM2 model!
- need $A_0^2 = 2m_{10}^2 = 4m_{16}^2$
- inverted scalar mass hierarchy: BFPZ
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$
  - $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ TeV
  - $m_{\tilde{t}_1},\ m_A,\ \mu \sim 1-2$ TeV
  - $m_{\tilde{g}} \sim 350-500$ GeV
- see Baer et al; Blazek et al.

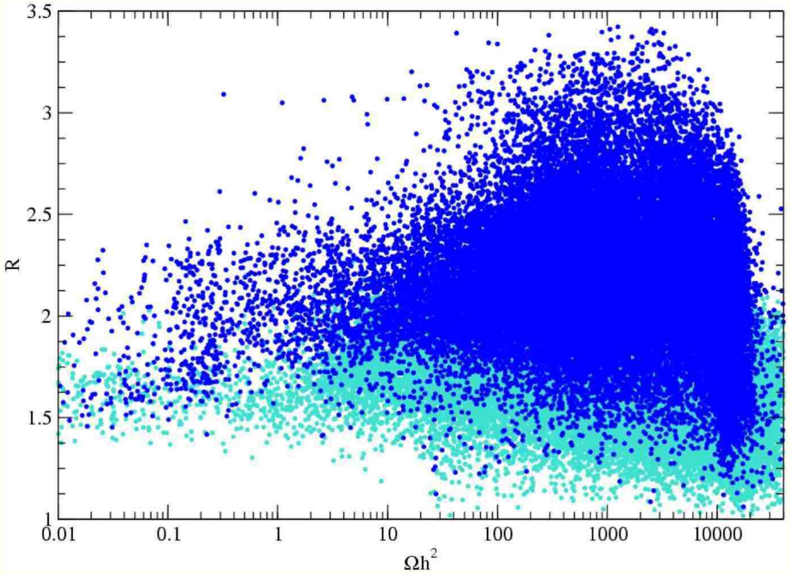


Top-down scan of NUHM2 p-space



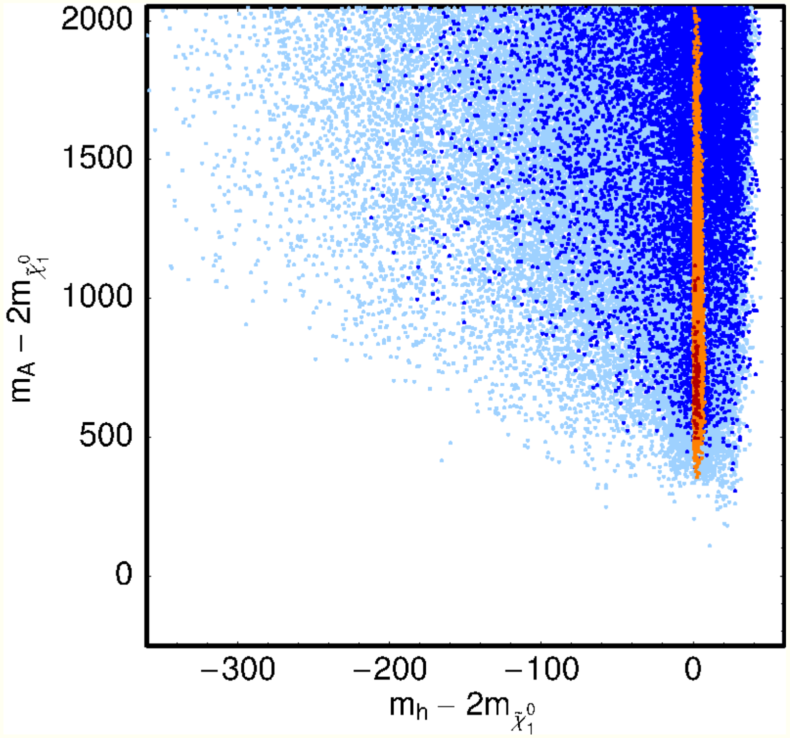
New analysis: MCMC approach (HB, Kraml, Sekmen, Summy)

Problem reconciling DM with Yukawa unification



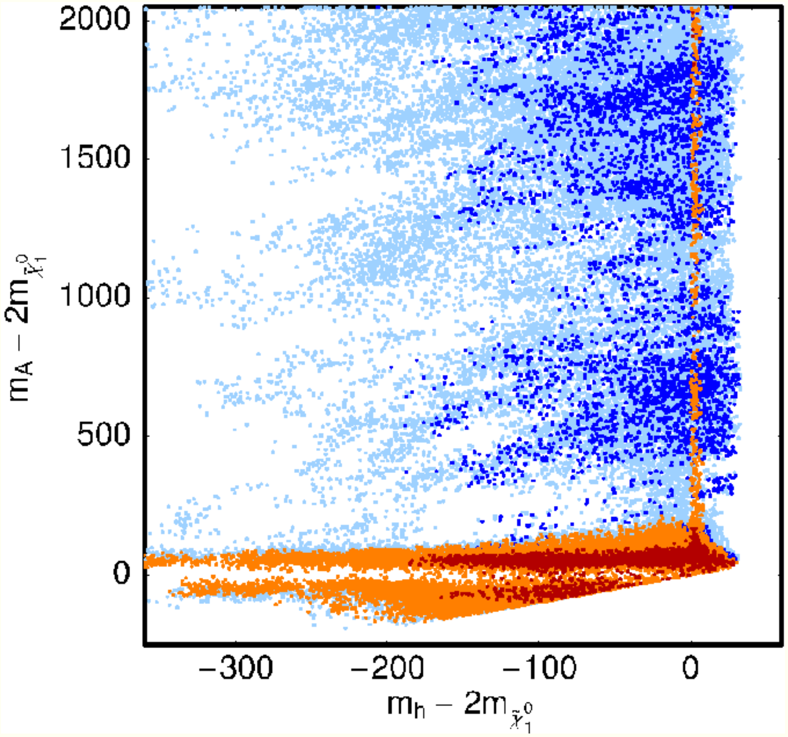
- one solution: axino DM instead of neutralino
- $\Omega_{\tilde{a}}h^2 \sim \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}}\Omega_{\widetilde{Z}_1}h^2$: $\Rightarrow$ warm DM
- also thermal component depending on T_R: $\Rightarrow$ CDM

MCMC scan: compromise solution with $m_{16} \sim 3$ TeV



- $\widetilde{Z}_1\widetilde{Z}_1$ annihilate through h resonance

Can generate BDR solutions with both WS/GS BCs



- $\widetilde{Z}_1\widetilde{Z}_1$ annihilate through A resonance
- comb. large $\tan\beta \sim 50$ and low m_A: excluded by $B_s \to \mu^+\mu^-$

Prediction of new physics at LHC from $SO(10)$ SUSYGUTs:

- gluino pair production with $m_{\tilde{g}} \sim 350 - 450$ GeV
- high b-jet multiplicity
- $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim 50 - 75$ GeV dilepon mas edge

Conclusions

- ⋆ Baryogenesis scenarios: constrained by ν/sparticle searches
- ⋆ Overwhelming evidence for CDM in the universe: identity unknown
- ⋆ Numerous candidate CDM particles from theory
- ⋆ WIMPs: thermal relic from Big Bang
- ⋆ SUSY $\widetilde{Z}_1$ is favored WIMP candidate, but many others
- ⋆ Detection at colliders: Tevatron, LHC, ILC; direct/indirect DM
- ⋆ SuperWIMPs: $\tilde{G}$ in SUSY; G in UED
- ⋆ models: mSUGRA; NUSUGRA; MMAMSB; $SO(10)$ with YU
- ⋆ We are on our way to unveiling the mysteries of baryogenesis and Dark Matter in next several years!